

AUSGeoid09 Performance in Mountainous Terrain: A Case Study in the Blue Mountains

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Abstract

AUSGeoid09 is the latest model used to convert Global Navigation Satellite System (GNSS) derived ellipsoidal heights to heights in the Australian Height Datum (AHD). While previous studies have evaluated the performance of the AUSGeoid09 model across Australia, such studies have not focused on mountainous regions in particular. This paper evaluates AUSGeoid09 in the Blue Mountains region of New South Wales from a practical user's point of view. Along a 90 km stretch of road incorporating flat to mountainous terrain, comparisons were undertaken between AUSGeoid09-derived heights and published AHD heights, using repeated Network Real Time Kinematic (NRTK) GNSS observations. The performance of AUSGeoid09 was also evaluated relative to its predecessor, AUSGeoid98, and the latest gravimetric model AGQG2009. It was found that AUSGeoid09 performs well across the study area and provides a significant improvement over AUSGeoid98. AUSGeoid09 generally allows AHD height determination at the ± 0.03 m level (1 sigma) in flat terrain and at the ± 0.06 m level (1 sigma) in mountainous terrain. However, across the entire study area, AUSGeoid09-derived AHD heights are consistently *lower* than the published AHD heights. Comparison of the results obtained with AUSGeoid09 against those using AGQG2009 in flat terrain illustrates the benefit that the introduction of the geometric component of AUSGeoid09 has had on the determination of AHD heights with satellite technology. However, for elevations above 500 m it appears that the geometric component *degrades* the fit to AHD in the study area, indicating that there is room for improvement in regards to future versions of the AUSGeoid model.

Keywords: AUSGeoid09, geoid model, height datum, AHD, NRTK, GNSS.

1 Introduction

Most countries have adopted Mean Sea Level (MSL) as zero height surface for their national vertical datum (e.g. Featherstone & Kuhn, 2006; Janssen, 2009). Height above MSL is crucial information for a wide range of applications, e.g. flood modelling, emergency management and engineering construction. In Australia, MSL was approximated as the basis of the Australian Height Datum (AHD) by setting to zero the average MSL values of 32 tide gauges around the country for a period of about two years that began in 1966 (Roelse et al., 1971). The national height datum is complemented by the Geocentric Datum of Australia 1994 (GDA94) for horizontal positions (ICSM, 2009).

More than 40 years after its inception, it is well known that shortcomings in the AHD realisation (AHD71 for mainland Australia and AHD83 for Tasmania) resulted in MSL not being coincident with the geoid at the tide gauges involved. These shortcomings included not considering dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), a lack of long-term tide gauge data, and the omission of observed gravity. This means that the reference surface for AHD is not a truly level (geopotential) surface, although it was intended to be so when created and is generally used as if it was level. In fact, AHD has variations from the level surface of 1.5 m across Australia and is therefore considered a third-order datum (Morgan, 1992; Featherstone & Filmer, 2012). However, for operational convenience and to avoid confusion, the non-level AHD continues to be used as a practical height datum that provides a sufficient approximation of the geoid for many applications. Consequently, in practice, AHD heights are often accepted as being equivalent to orthometric heights.

Over the last two decades, Global Navigation Satellite System (GNSS) technology has become the primary positioning tool due to its accuracy, speed and accessibility. In particular, Network Real Time Kinematic (NRTK) GNSS is being utilised for a wide range of surveying, mapping, agriculture, mining and construction applications, providing users with instant and highly accurate position information over distances of several tens of kilometres. The advantage of NRTK is its ability to provide corrections (accounting for atmospheric and satellite orbit errors) that are based on a Continuously Operating Reference Station (CORS) network rather than a single reference station (e.g. Wang et al., 2010; Janssen & Haasdyk, 2011; Penna et al., 2012).

GNSS-based heights refer to a reference ellipsoid, i.e. a purely mathematical representation of the earth, and therefore have no physical meaning. In most practice, however, heights are required that correctly reflect the flow of water (or at least sufficiently approximate it), e.g. for flood modelling or drainage and pipeline design. Hence, a reliable geoid model is required to derive AHD heights from measured ellipsoidal heights (e.g. Kearsley, 1988). These geoid models provide N values (N), also known as geoid undulations or geoid-ellipsoid separations, that can be used to convert GNSS-derived ellipsoidal heights (h) to AHD heights (H) and vice versa (provided N and h refer to the same ellipsoid):

$$H = h - N \quad (1)$$

For many years, the use of geoid models (or quasigeoid models – see Vaniček et al. (2012) for a discussion of the difference) has helped GNSS users to compute AHD heights from ellipsoidal heights. In the Australian context, AUSGeoid09 is the latest model that best fits AHD (Brown et al., 2011; Featherstone et al., 2011).

While the performance of AUSGeoid09, along with the improvements it provides over its predecessor AUSGeoid98, have been investigated previously (e.g. Janssen & Watson, 2010; Brown et al., 2011), these studies have not focused on mountainous regions. Considering that gravity can change dramatically within a few kilometres on the earth's surface in Australia (Darbeheshti & Featherstone, 2009), especially in mountainous terrain, and that observed gravity data are generally sparse in these areas (usually observed along the roads to allow easy access), it is necessary to investigate mountainous regions in particular.

This paper evaluates AUSGeoid09 performance in the Blue Mountains in New South Wales (NSW), from a practical user's point of view, using NRTK GNSS-derived ellipsoidal heights and published AHD heights. AUSGeoid09 is compared to its gravimetric component (AGQG2009) and its predecessor (AUSGeoid98) in the study area.

2 AUSGeoid09

AUSGeoid09 was released in March 2011 by Geoscience Australia, replacing the previous model AUSGeoid98 (Featherstone & Guo, 2001). Both models refer to the GRS80 ellipsoid, which was adopted as the reference ellipsoid for GDA94, and cover the same geographical area between 108°E and 160°E longitude and between 8°S and 46°S latitude. However, AUSGeoid09 is provided as a 1' by 1' grid (approximately 1.8 by 1.8 km), making it four times denser than its predecessor (Featherstone et al., 2011).

Previous versions of AUSGeoid were predominantly gravimetric-only quasigeoids, and it was assumed that these were sufficiently close approximations of AHD – an assumption we now know to be incorrect. In contrast, AUSGeoid09 is a combined gravimetric quasigeoid plus a geometric model, providing a direct connection to AHD and thereby allowing a more reliable determination of AHD heights from GNSS observations (Brown et al., 2011). The empirically derived geometric component accounts for the offset between the gravimetric quasigeoid (AGQG2009 – see Featherstone et al., 2011) and AHD, which is predominantly caused by AHD not taking into account sea surface topography including the differential heating of the oceans. Since the warmer or less dense

water off northern Australia is about 1 metre higher than the cooler or denser water off southern Australia, AHD is about 0.5 m above the quasigeoid in northern Australia and roughly 0.5 m below the quasigeoid in southern Australia (Janssen & Watson, 2010; Brown et al., 2011). The introduction of the geometric component takes care of most of this 1-metre trend across Australia (0.6-metre trend across NSW), thereby providing a better overall fit to AHD.

AUSGeoid09 has been shown to convert ellipsoidal heights to AHD heights with an accuracy of ± 0.03 m (1 sigma) across most of Australia, with the exception of some pocket areas where the misfit can be larger than ± 0.1 m due to errors caused by factors such as the ageing levelling network, geoid height variability or data deficiency (Brown et al., 2011). Using a more practical approach, Janssen & Watson (2010) found that AUSGeoid09 generally allows GNSS-based height determination in NSW at the ± 0.05 m level (1 sigma). In contrast, its predecessor AUSGeoid98 only provides an absolute accuracy of ± 0.4 m (Featherstone & Guo, 2001; Featherstone et al., 2001).

A recent study by Sussanna et al. (2014) investigated the performance of AUSGeoid09 in two mountainous regions of NSW, based on two sizable GNSS network adjustment datasets. In the Mid Hunter (elevations ranging between 20 m and 1,400 m), AUSGeoid09 was able to deliver AHD heights at the ± 0.04 m level (1 sigma) and provided a substantial improvement over its predecessor, clearly demonstrating the benefits of its geometric component on GNSS-derived AHD height determination. In the Snowy Mountains (elevations ranging from 200 m to 2,200 m), AHD height determination was achieved at the ± 0.07 m level (1 sigma) and moderate improvement over AUSGeoid98 was evident. However, a slope was detected for AUSGeoid09 residuals, and it appears that the geometric component may have overcompensated for sea surface topography in this area.

3 Testing methodology

Owing to the increased use of GNSS CORS networks, the absolute accuracy of N values is now more important than ever for AHD height determination using satellite positioning techniques (Janssen & Watson, 2010). In this paper, the performance of the AUSGeoid09 model in mountainous terrain is evaluated in the Blue Mountains, based on the comparison of repeated NRTK GNSS observations and published AHD heights.

A number of spirit-levelled benchmarks with known AHD heights of sufficient quality (Class LB Order L2 or better) on public record in the Survey Control Information Management System (SCIMS) were used as test points. SCIMS is the state's database containing about 250,000 survey marks across NSW, including coordinates, heights and other information (Kinlyside, 2013). For a discussion of the terms class and order, the reader is referred to ICSM (2007) and Dickson (2012). It should be noted that the published AHD heights of the benchmarks used as test points are not guaranteed to be error-free. Consequently, they can only be treated as benchmarks defining AHD in the study area (and comparisons are thus made to the national height datum), not as representing true orthometric heights.

In order to replicate a practical scenario, these test points were occupied multiple times using the NRTK GNSS technique to obtain ellipsoidal heights. NRTK observations were based on CORSnet-NSW (e.g. Janssen et al., 2013), an expanding state-wide network of more than 160 GNSS CORS providing fundamental positioning infrastructure for New South Wales (Figure 1). As recommended by Janssen & Haasdyk (2011), the windowing technique was applied to increase reliability of the resulting positions and each test point was re-observed several times (using a tripod for stability) to ensure redundancy and allow for changes in satellite geometry between occupations.

3.1 Windowing technique

The windowing (or averaging) technique is often applied to improve the positioning result for real-time applications if the GNSS rover is allowed to remain stationary for a short period of time. Windowing is achieved by determining the average of several epochs observed at a point, thus increasing the reliability of the resulting position. It is important to note that windowing reduces the effect of extreme, short-lived outlier observations, but can still produce results that are significantly offset from the mean. Janssen & Haasdyk (2011) suggest observing for 1-2 minutes to obtain an averaged position in order to reduce the effects of individual coordinate solution outliers. If high-quality vertical coordinates are required or the user is distant from the nearest CORS, it is advised to use a 2-minute observation window. It was also shown that double occupations, i.e. re-observing each point after waiting about 10-30 minutes or more, increases the reliability of the resulting position.

In a preliminary test, the benefit of using the windowing technique in this study was assessed by occupying several test points multiple times and collecting NRTK-based positions for short (10 epochs) and longer (3 minutes) observation windows. The standard deviations of the ellipsoidal height observations on each test point were then investigated to determine which observation window length should be used in the following analysis.

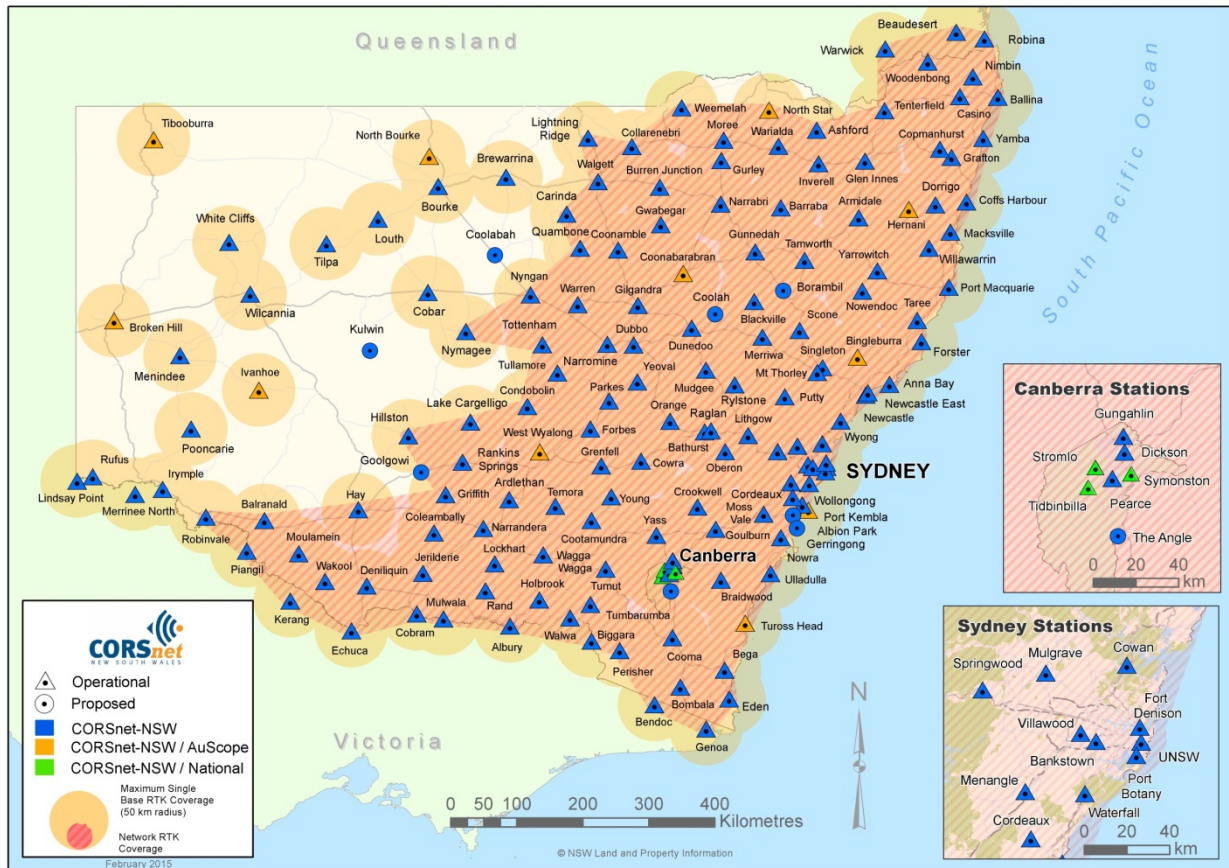


Figure 1: CORSnet-NSW network map as of February 2015 (LPI, 2015).

3.2 Evaluation of AUSGeoid09 in flat and mountainous terrain

Using equation 1, observed NRTK GNSS-derived ellipsoidal heights (h) were converted to AHD heights (H) using three quasigeoid models (i.e. AUSGeoid09, AUSGeoid98 and AGQG2009) and compared to the published AHD height (H_{AHD}) at each test point. The test points were chosen to ensure that an even number of these were located in flat terrain and mountainous terrain in order to allow evaluation of AUSGeoid09 performance in both terrain conditions.

Descriptive statistics were used to quantify the performance of AUSGeoid09 in determining AHD heights from GNSS observations in the study area. Since it is necessary to consider residuals of different signs, the Root Mean Square (RMS) was also utilised. Furthermore, a comparison between AUSGeoid09 and its predecessor AUSGeoid98 as well as AUSGeoid09's gravimetric component (AGQG2009) was performed to quantify the improvement gained in mountainous areas and investigate the effect of introducing the geometric component.

4 Study area

The performance of AUSGeoid09 in mountainous terrain was evaluated in the Blue Mountains located west of Sydney, NSW. The study area incorporates 23 test points along Windsor Road and Bells Line of Road between Castle Hill in the east and Lithgow in the west (Figure 2). It exhibits initially flat terrain (blue test points) changing into substantially undulating terrain with large differences in elevation (red test points), thus representing typical mountainous terrain conditions encountered in Australia (Figure 3).

The eastern half of the study area follows Windsor Road, connecting the Sydney suburb of Castle Hill in the east with the townships of Windsor and Richmond towards the west. This line is approximately 40 km long and exhibits relatively flat terrain, gently changing between about 10 m and 125 m in elevation. The western half of the study area is located along Bells Line of Road, a winding mountain road connecting the townships of Richmond and Lithgow. This line is approximately 50 km long and exhibits undulating terrain with elevations ranging from about 185 m to 1,100 m. AUSGeoid09 N values range from 23 m to 26 m in the study area, steadily increasing from east to west.

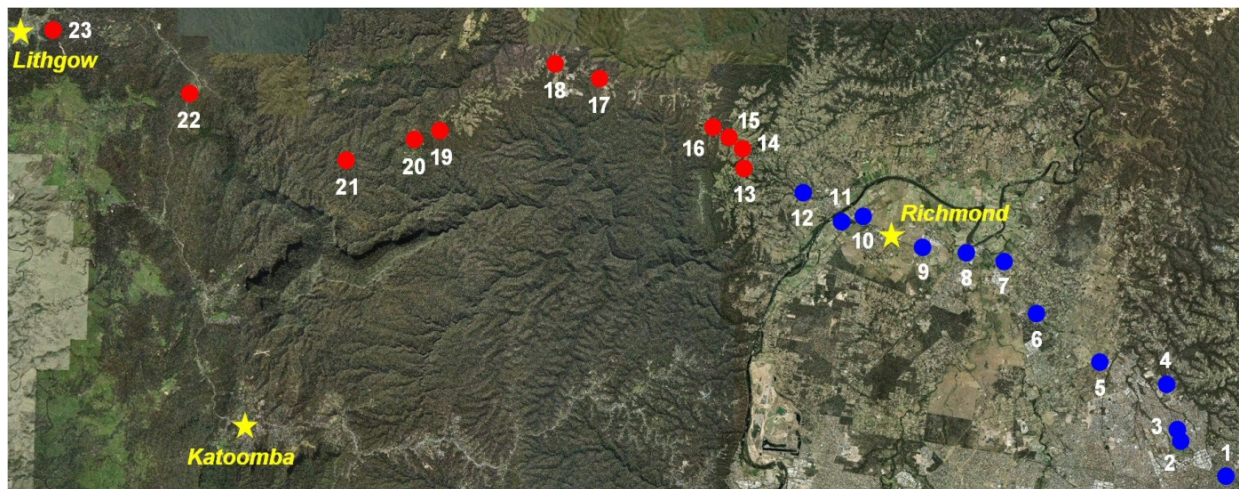


Figure 2: Location of the test points (SCIMS benchmarks) in the study area.

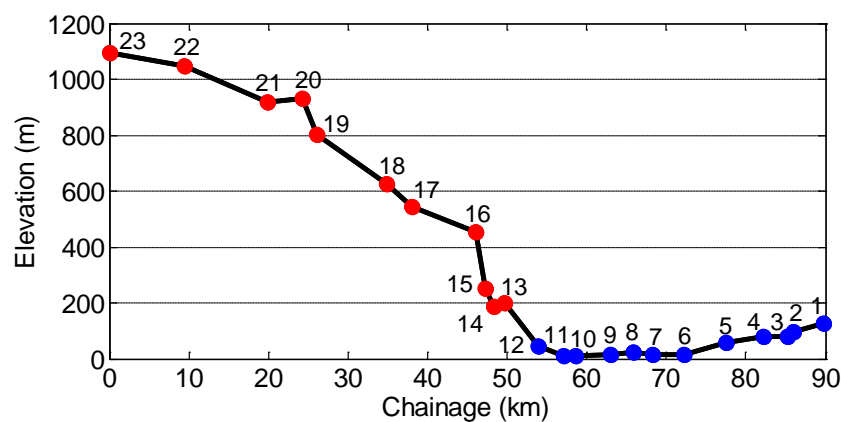


Figure 3: Cross section of the test points, indicating the range in elevation (AHD height).

5 Data collection and analysis

5.1 Field work issues

Naturally, it is desired to obtain the largest possible sample of high-quality test points and utilise high-precision positioning techniques in order to provide a solid base for analysis. In practice, however, compromises have to be made due to constraints in regards to time and resources. While a lot of first-order levelled benchmarks (LAL1) are available close to Sydney, most of these have an 'unknown' classification for the horizontal class and order (UU). This means that the published horizontal coordinates are generally only accurate to several tens of metres, in some cases up to 200 m. Furthermore, the locality sketches for most of these benchmarks were drawn in the early 1960s (when the benchmarks were placed) and did not have many useful references to locate the marks 50 years later. While SCIMS indicates whether a mark has been 'destroyed' or 'not found' or even 'found intact', the marks that have not been classified as such are not guaranteed to still exist. Most of the benchmarks were placed on the side of the road and not located near identifiable features such as road intersections, houses or other physical structures. References mainly consisted of fencing, power poles and mile posts. Understandably, these features have been replaced, removed or have deteriorated over time.

As a result, many of these marks could not be recovered and second-order levelled marks (LBL2) had to be used instead. Along Bells Line of Road, only 8 marks were found out of the initially selected 25 benchmarks, and the dataset was therefore expanded with three LBL2 marks towards the east (Kurrajong) to obtain a larger sample for analysis. While the majority of marks used along Bells Line of Road are classified LAL1, all 12 marks used along Windsor Road are classified LBL2.

Another issue that arose (as expected) was the inability to observe directly over a benchmark due to limited skyview or multipath issues. This problem was overcome by placing an arbitrary (eccentric) mark, i.e. nail in bitumen or hard ground, a short distance away at a location with more favourable observing conditions. The AHD height of the benchmark was then transferred to the arbitrary mark using a total station, measuring four sets of reciprocal zenith angles and slope distances to determine the vertical distance between the two marks. A spirit level and staff were not used because this could not be achieved by only one person in the field. This procedure was required for four test points along Bells Line of Road (SS342, SS341, SS336 and SS319). Finding a larger number

of the initially selected marks would have increased the sample size and may have reduced the percentage of benchmarks observed using arbitrary marks. Fortunately, field work was not hampered by encounters with native wildlife (Janssen, 2012).

5.2 Windowing technique and ellipsoidal height quality

A preliminary test was undertaken to assess the benefit of using the windowing technique in this study. A number of test points were occupied several times (generally between 30 minutes and several days apart), collecting NRTK-based positions based on 10 epochs of data as well as 3 minutes of data. Table 1 states the number of occupations and the standard deviation (STD) of the ellipsoidal height observations on each test point. It can be seen that the longer averaging window improves the mean standard deviation slightly and appears to remove two relatively large values of 0.030 m and 0.041 m. Based on these findings, it was decided to occupy all remaining test points for 3-minute observation windows.

Table 1: Assessment of the windowing technique based on the standard deviation of ellipsoidal height observations (STD given in metres).

Test Point	Mark ID	No. Occ. (10 epoch)	No. Occ. (3 min)	STD (h) (10 epoch)	STD (h) (3 min)
17	SS342	4	3	0.030	0.017
18	SS341	8	8	0.009	0.017
19	SS336	6	7	0.041	0.022
20	SS335	6	8	0.017	0.023
21	SS332	8	8	0.016	0.025
22	SS44364	4	4	0.010	0.013
23	SS319	6	6	0.013	0.007
			Mean	0.020	0.018

The average quality of all observed GNSS ellipsoidal heights indicated by the GNSS rover was $0.014 \text{ m} \pm 0.003 \text{ m}$ along Windsor Rd (flat terrain) and $0.025 \text{ m} \pm 0.009 \text{ m}$ along Bells Line of Road (mountainous terrain). However, research has shown that these quality indicators can be overly optimistic (e.g. Wang et al., 2010; Janssen & Haasdyk, 2011). In order to get a better appreciation of the quality of the observed ellipsoidal heights, the vertical precision of all 3-minute occupations on each test point was investigated. An average STD of 0.010 m was achieved in flat terrain (ranging from 0.001 m to 0.027 m), while the average STD increased to 0.019 m (ranging from 0.002 m to 0.042 m) in mountainous terrain. These findings, along with a thorough investigation of the collected data, provided confidence that the dataset was free of outliers.

5.3 Flat terrain: Windsor Road

Each test point was occupied at least three times with NRTK GNSS using CORSnet-NSW and 3-minute observation windows. The average ellipsoidal height was determined, and AHD heights were calculated by applying the N values from three different quasigeoid models, i.e. AUSGeoid09, AUSGeoid98 and AGQG2009. The AGQG2009 model was kindly provided by Geoscience Australia as it is not readily available to the public in order to avoid confusion between this gravimetric-only model and the published AUSGeoid09. The derived AHD heights for each test point were then compared to the published SCIMS values, which were used as control in this study, to evaluate the performance of AUSGeoid09 and compare the models.

Table 2 shows the differences between NRTK GNSS-derived AHD heights (using the three quasigeoid models) and published AHD heights (AHD_{SCIMS}) for the test points situated in flat terrain along Windsor Road. Descriptive statistics show that AUSGeoid09 allows AHD height determination with an accuracy of about $-0.026 \pm 0.016 \text{ m}$ (1 sigma) in this part of the study area. As all differences are negative, the Root Mean Square (RMS) provides a similar value, i.e. 0.030 m. Using AUSGeoid09 rather than its predecessor AUSGeoid98 resulted in substantially better agreement with published AHD heights, e.g. illustrated by the RMS dropping from 0.211 m to 0.030 m – an improvement by a factor of 7.0.

Comparing the results obtained with AUSGeoid09 against those using AGQG2009 illustrates the benefit that the introduction of the geometric component of AUSGeoid09 has had on the determination of AHD heights with satellite positioning technology. In this case, the RMS improved by a factor of 2.5, dropping from 0.076 m to 0.030 m. For all test points, AUSGeoid09 provided heights that are about 30-50 mm closer to the published AHD values than those obtained using AGQG2009. This improvement is consistent with the geometric component of AUSGeoid09 generally amounting to about -0.05 m or less in this area (Brown et al., 2011), considering that a negative geometric component results in a smaller N value and therefore a larger derived AHD height. While the range of differences for all three models remains at a similar level of 0.06 m, it is obvious that AUSGeoid09 provides heights that are much closer aligned with the published values than the other two models. In other words,

the evolution from AUSGeoid98 to AGQG2009 and AUSGeoid09 has significantly improved the fit between GNSS-derived and published AHD heights.

Table 2: Agreement of NRTK GNSS-derived AHD heights (using different quasigeoid models) to SCIMS in flat terrain (Windsor Road) – all values stated in metres.

Test Point	Mark ID	Class/Order	No. Occ. (3 min)	AHD _{SCIMS}	Δ AHD _{AG09}	Δ AHD _{AG98}	Δ AHD _{AGQG09}
1	SS61355	LBL2	3	126.160	-0.037	-0.203	-0.092
2	PM31480	LBL2	4	95.893	-0.026	-0.200	-0.081
3	SS44875	LBL2	3	79.272	-0.015	-0.190	-0.071
4	SS17350	LBL2	4	77.988	-0.020	-0.200	-0.075
5	PM29273	LBL2	4	59.921	-0.031	-0.218	-0.087
6	PM67548	LBL2	6	14.102	-0.028	-0.220	-0.081
7	PM41505	LBL2	6	14.045	-0.035	-0.230	-0.087
8	SS10399	LBL2	6	24.293	-0.004	-0.198	-0.052
9	PM45758	LBL2	6	17.167	-0.015	-0.204	-0.059
10	SS75618	LBL2	4	11.445	-0.037	-0.225	-0.073
11	PM74693	LBL2	3	11.552	-0.062	-0.251	-0.095
12	PM45486	LBL2	3	44.985	-0.002	-0.190	-0.031
				Mean	-0.026	-0.211	-0.074
				STD	0.016	0.018	0.019
				RMS	0.030	0.211	0.076
				Min	-0.062	-0.251	-0.095
				Max	-0.002	-0.190	-0.031
				Range	0.060	0.061	0.064

5.4 Mountainous terrain: Bells Line of Road

The same procedure was applied to the remainder of test points, located in mountainous terrain along Bells Line of Road. The resulting differences between NRTK GNSS-derived AHD heights (using the three quasigeoid models) and published AHD heights (AHD_{SCIMS}), along with descriptive statistics, are shown in Table 3.

It can be seen that AUSGeoid09 allows AHD height determination with an accuracy of about -0.060 ± 0.039 m (1 sigma) in this part of the study area. As all differences are negative, the Root Mean Square (RMS) provides a similar value, i.e. 0.071 m. Again, AUSGeoid09 provides substantially better agreement with published AHD heights than its predecessor AUSGeoid98, e.g. illustrated by the RMS dropping from 0.174 m to 0.071 m – an improvement by a factor of 2.5.

It should be noted that test points 18 & 23 (SS341 & SS319) show much larger discrepancies (at the 120 mm level) to the published AHD heights than all other test points in the study area. This suggests that the published heights of these marks may be incorrect (possibly due to mark movement) or deficiencies may be present in the quasigeoid model used. At SS341, this substantial disagreement is evident across all three models investigated, and neighbouring marks do not exhibit similar behaviour, supporting that subsidence may be the cause. At SS319, the AGQG2009-derived AHD height agrees much better (at the 40 mm level) with the published AHD height, suggesting that in this case the discrepancy may not be due to mark subsidence but rather be caused by deficiencies in the geometric component of AUSGeoid09. In both cases, however, the limited data available precludes a definitive answer.

If these two test points were removed from the analysis, the accuracy of AUSGeoid09-derived AHD heights improves to -0.046 ± 0.025 m (1 sigma), while the RMS improves to 0.052 m and the range drops from 0.111 m to 0.070 m. In addition, AUSGeoid09 improves the fit to published AHD by a factor of 3.2 over its predecessor AUSGeoid98, with the RMS dropping from 0.164 m to 0.052 m.

Comparison of the results obtained with AUSGeoid09 and AGQG2009 shows that, contrary to the findings in flat terrain, the introduction of AUSGeoid09's geometric component overall has not had a positive effect in this part of the study area. While the range of differences from published AHD heights improved slightly, the RMS actually increased by a factor of 1.4, from 0.050 m to 0.071 m. (If test points 18 & 23 were removed from the analysis, the RMS increases by a factor of 1.3, from 0.039 m to 0.052 m.) Closer inspection reveals that for elevations below 500 m, the geometric component improved the fit to published AHD heights by about 15 mm. However, for elevations above 500 m, the geometric component appears to degrade the fit by about 10-30 mm. For elevations above 1,000 m, this negative effect is even larger, exceeding 70 mm. While it is recognised that the sample size is small, this may indicate possible problems with the geometric component at high elevations – not surprisingly, as it is well known that suitable datasets for the generation of the geometric component are notoriously sparse in mountainous regions. It is also understood that the gravimetric geoid is weaker in mountainous regions because (1) gravity data

are limited, (2) existing gravity data are biased along the ridges (roads) and creeks for ease of access, and (3) the terrain effect is less well modelled in regions of large elevation changes in topography.

Table 3: Agreement of NRTK GNSS-derived AHD heights (using different quasigeoid models) to SCIMS in mountainous terrain (Bells Line of Road) – all values stated in metres.

Test Point	Mark ID	Class/Order	No. Occ. (3 min)	AHD _{SCIMS}	Δ AHD _{AG09}	Δ AHD _{AG98}	Δ AHD _{AGQG09}
13	PM45491	LBL2	3	201.224	-0.019	-0.184	-0.037
14	PM45501	LBL2	3	186.888	-0.027	-0.191	-0.045
15	PM1677	LAL1	4	251.366	-0.044	-0.197	-0.060
16	SS347	LAL1	3	454.364	-0.050	-0.184	-0.064
17	SS342	LAL1	3	542.686	-0.014	-0.133	-0.009
18	SS341	LAL1	8	626.173	-0.122	-0.230	-0.109
19	SS336	LAL1	7	801.360	-0.073	-0.165	-0.038
20	SS335	LAL1	8	932.277	-0.071	-0.147	-0.032
21	SS332	LAL1	8	918.139	-0.034	-0.111	0.017
22	SS44364	LBL2	4	1046.127	-0.084	-0.144	-0.010
23	SS319	LAL1	6	1092.527	-0.125	-0.189	-0.043
				Mean	-0.060	-0.170	-0.039
				STD	0.039	0.034	0.033
				RMS	0.071	0.174	0.050
				Min	-0.125	-0.230	-0.109
				Max	-0.014	-0.111	0.017
				Range	0.111	0.119	0.126

Investigating the effect of the geometric component in more detail, it is interesting to note that the improvement of fit to published AHD steadily decreases from east to west in the study area, from about 55 mm in the western outskirts of Sydney to zero near Kurrajong. Heading further west through the Blue Mountains, the geometric component increasingly *degrades* (almost linearly with distance) the GNSS-based determination of AHD heights in the study area, culminating in up to 80 mm at the highest elevations near Lithgow (Figure 4). This can be explained by the decreasing density of datasets available for the empirical determination of the geometric component away from metropolitan areas. It is also interesting to note that across the entire study area, featuring both flat and mountainous terrain, AUSGeoid09-derived AHD heights are always *lower* than the published AHD heights. This indicates that there is room for improvement in regards to future versions of the AUSGeoid model, provided additional datasets are collected in this region.

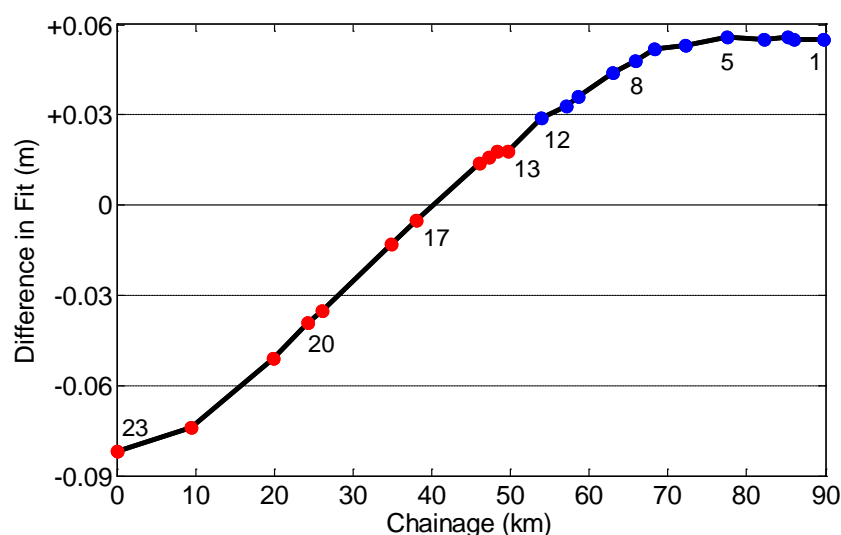


Figure 4: Difference in fit to published AHD heights between AUSGeoid09 and AGQG2009 derived AHD heights in the study area. Positive values indicate improvement of fit due to the geometric component.

5.5 Cross sections

In order to provide a visual perspective of the results obtained in the study area, cross sections were generated showing published AHD heights and NRTK GNSS-derived AHD heights based on the three quasigeoid models investigated (Figure 5). The cross sections run from left to right in a west-to-east direction and have been scaled and exaggerated (separately for each part of the study area) to allow a clearer visual comparison.

Across both terrain types, it is clearly evident that AUSGeoid09 provides a far better fit to published AHD values than its predecessor AUSGeoid98. In flat terrain, AUSGeoid09-derived heights are consistently closer to published AHD than AGQG2009-derived heights, showing the benefit of the geometric component. The shape of all quasigeoid-derived cross sections is very similar to the shape of AHD in this part of the study area. In mountainous terrain, the shape of all quasigeoid-derived cross sections is very similar but deviates from the shape of published AHD in several cases. This behaviour is most obvious at test point 18 (SS341), a mark that has already been identified as possibly being affected by subsidence. The cross sections also visualise that the geometric component of AUSGeoid09 appears to increasingly degrade the fit to published AHD for the marks investigated west of test point 17.

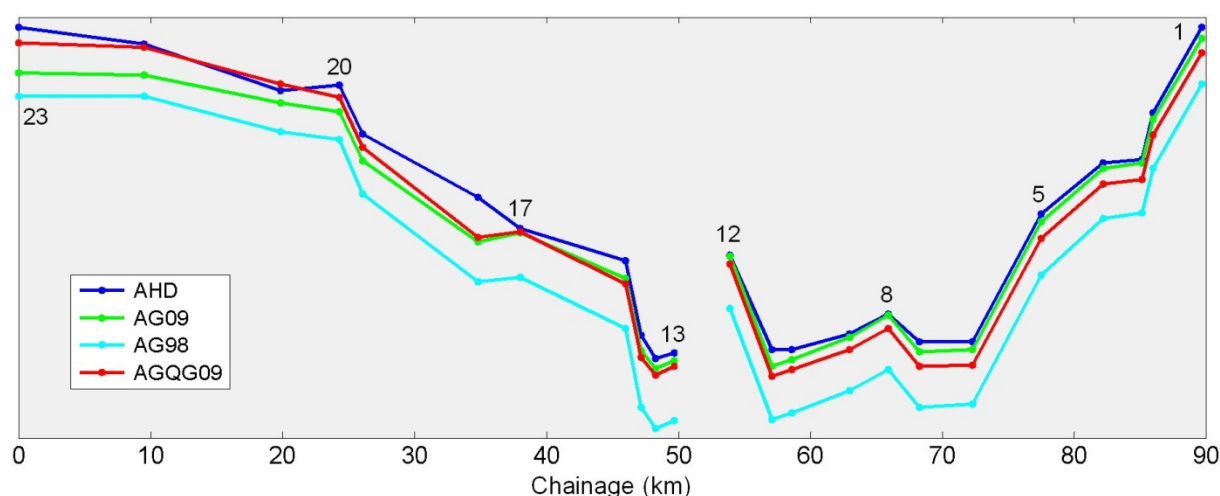


Figure 5: Cross sections showing published AHD heights and NRTK GNSS-derived AHD heights using different quasigeoid models, separately scaled and exaggerated in each part of the study area.

6 Conclusion

This paper has evaluated the performance of AUSGeoid09 in the Blue Mountains region of New South Wales, from a practical user's point of view. Along a 90 km stretch of road incorporating flat to mountainous terrain, comparisons were undertaken between AUSGeoid09-derived heights and published AHD heights, using repeated NRTK GNSS observations on 23 test points. The performance of AUSGeoid09 was also evaluated relative to its predecessor, AUSGeoid98, and the latest gravimetric quasigeoid model AGQG2009.

In a preliminary test, it was confirmed that the windowing technique can reduce the effect of extreme, short-lived outlier observations and increase the reliability of NRTK GNSS-derived positions. Consequently, it was decided to occupy the test points for 3-minute observation windows.

It was shown that AUSGeoid09 performs well across the study area and provides a significant improvement over AUSGeoid98. AUSGeoid09 generally allows AHD height determination at the ± 0.03 m level (1 sigma) in flat terrain and at the ± 0.06 m level (1 sigma) in mountainous terrain. This level of accuracy agrees well with findings reported in previous studies and is very encouraging, particularly in light of GNSS technology and CORS networks being increasingly used to provide vertical control. However, across the entire study area, AUSGeoid09-derived AHD heights were found to be consistently *lower* than the published AHD heights.

Comparison of the results obtained with AUSGeoid09 against those using AGQG2009 in flat terrain illustrates the benefit that the introduction of the geometric component of AUSGeoid09 has had on the determination of AHD heights with satellite positioning technology. However, it was also found that the geometric component appears to *degrade* the fit to AHD for elevations above 500 m in the study area. This indicates that there is room for improvement in regards to future versions of the AUSGeoid model.

It is recognised that this study is based on a much smaller sample than initially planned. Consequently, it is not suggested that the results presented can be generalised to apply to other mountainous regions. The availability of higher-quality horizontal coordinates for first-order benchmarks in SCIMS would have been very beneficial in regards to locating a larger number of test points in the available time frame. Levelled benchmarks are important for the maintenance of the national height datum, and it should therefore be possible to locate these marks more easily. It is recommended that this well-known issue be addressed by the custodians of SCIMS in the future, particularly in

light of the planned introduction of a next-generation datum for Australia (Haasdyk et al., 2014) and the increasing need to preserve existing survey mark infrastructure (de Belin, 2012; Ward, 2014).

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